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Difference method to search for the anisotropy of the primary cosmic radiation

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Abstract

The original difference method for the search of an anisotropy of the primary cosmic radiation at the knee region of its energy spectrum is considered. Its methodical features and properties are analyzed. It is shown that the method, in which not an intensity but a properties of the particle fluxes are investigated, is stable against the random experimental errors and allows to separate anomalies connected with the laboratory coordinate system from anomalies in the celestial coordinate system. The method uses the multiple scattering of the charged particles in the magnetic fields of the Galaxy to study the whole celestial sphere including the regions outside the line of sight of the installation.

Key words: cosmic rays, break of primary energy spectra, diffusive transfer, experiment, difference method, nearby source

1 Introduction

The difference method is developed for the study of the nature of a break (knee) in the charged particle energy spectrum of the primary cosmic radiation (PCR). The spectrum is well described by a power law with an index of 2.7 from the energy $\sim 10^{10}$ eV up to $\sim 3 \times 10^{15}$ eV where the index increases rapidly to 3.1. From its discovery in 1958 [1], the nature of the knee is still the subject of intensive discussions due to its importance for understanding the origin of the high energy cosmic radiation.

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In this paper we consider three widely discussed astrophysical models describing the behavior of the PCR in this energy range:

- The most popular is the diffusion model [2], in which the knee appears as a result of the increased leakage of particles from the Galaxy with the rising energy. Since magnetic fields bend heavy nuclei stronger than light nuclei, protons leave the Galaxy first followed later by heavier nuclei.
- The limited energy model [3], which suggests that the knee reflects the maximum energy to which protons are accelerated in the shells of Galactic supernova remnants.
- The model of a nearby source [4], where the spectrum of particles from this source is superimposed on the smooth Galactic spectrum creating an excess in the knee region which causes the break of its energy spectrum. The source has to be rather close so that its particles do not mix up with particles from other sources.

The choice between models can be made using the anisotropy of PCR particles coming to the Earth which is located approximately at the half of the radius of the Galaxy. Starting from general reasons it is possible to consider that if the anisotropy is found in the Center – Anticenter direction of the Galaxy, the most probable is the diffusion model since the particle flux from the Center has to exceed a flux to the Center above the knee.

If the anisotropy is found in another direction, the model of the nearby source located in this direction is most probable.

If the preferred and statistically reliable directions are not found it means that the model of limited acceleration is realized with its uniform distribution of the sources in the Galaxy.

The intermediate results depending on a contribution of the different models are also possible.

So far a reliable experimental confirmation of any model is not obtained and the measured anisotropy of the PCR intensity with the primary energy $10^{14} - 10^{16}$ eV is not bigger than one percent [5] which is comparable with the errors magnitude.

First of all this small anisotropy is due to a mixing of the trajectories of charged particles by the chaotic magnetic fields. This is why the propagation of PCR particles in the Galaxy is similar to the large-scale diffusive transport. It is also well known that, for equal conditions, nuclei with different masses are scattered differently by the magnetic fields. Therefore, a special method to study not the intensity, but the property of the particle fluxes was suggested and developed.

2 The difference method

This method of the analysis of the experimental data [6,7] initially takes into account the diffusive character of the PCR propagation in the Galaxy and has a high sensitivity. The method was specially developed to search for the anomalies and analyses not the intensity of the particle fluxes from different parts of the sky but anomalies of the PCR mass composition. At the same time the multiple scattering of particles in the Galaxy (diffusion) does not prevent but even helps to register PCR from the sources located outside the view of the experimental installation. The main condition for the application of the method is a stable work of the installation independent of the daytime, a season and throughout a year.

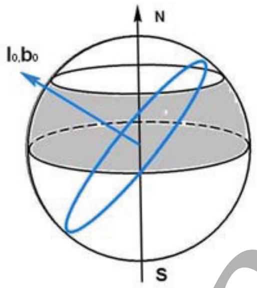


Fig. 1. An illustration of the partition of the celestial sphere on two parts in the equatorial coordinate system. The arrow is the direction being studied, the perpendicular plane to the arrow is border of the partition.

The study of the high energy PCR particles with ground based installations is carried out by detecting the extensive air showers (EAS) generated by these particles. In the laboratory coordinate system experimental installations have a limited sector for the registration of the PCR particles around a zenith. However, because of the Earth's rotation they can scan a rather significant part of the celestial sphere.

The essence of the method is as follows: the arbitrary directions (l_0, b_0) are given in the celestial coordinates. Then, around each of them, the cone is built with the calculated aperture angle ψ_0 to divide all the statistics of events in two equal sets - events which are inside the cone, and all the other outside the cone: $n^{in} = n^{out}$. For both sets the distributions of the analyzable parameter are built for the same distribution bins of the parameter. These distributions are subtracted from each other with the calculation of χ^2/J. Here J is the number of the degrees of freedom.

$$\chi^2 = \sum_i \left(\Delta_i / \sigma_i \right)^2, \tag{1}$$

where

$$\Delta_i = m_i^{in} - m_i^{out} \quad (2)$$

is the difference between the distributions in the bin i with the error

$$\sigma_i = \sqrt{m_i^{in} + m_i^{out} + 1} = \sqrt{n_i + 1} \approx \sqrt{n_i} \quad (3)$$

calculated from the Poisson distribution. The total number of events n_i and σ_i for the bin i does not depend on the given angles (l_0, b_0). It is crucially important for the comparison of the χ^2/J values between themselves to search for the maximum of χ^2/J. The mass compositions of the PCR, coming from the opposite directions, are most different in the direction where χ^2/J is maximal. It can be seen from the formulae (1)-(3) that, calculated in this way, the χ^2/J values for (l_0, b_0) and opposite $(l_0 + 180°, -b_0)$ directions are equal as σ_i and $|\Delta_i|$ are equal for all the bins. Therefore the equality $n^{in} = n^{out}$ allows to study the whole celestial sphere within the sensitivity of the method using an installation with a limited observation region. However, it does not allow to distinguish the directions (l_0, b_0) from $(l_0 + 180°, -b_0)$.

The separation of the celestial sphere in the equatorial coordinate system is shown in Fig. 1. In this system, the main plane – the plane of the celestial equator – coincides with the plane of the Earth's equator, so that the geographic latitude on Earth coincides with the celestial declination. The GAMMA installation (p. 5-6) is at 40° Northern Hemisphere. It is located in the center of the sphere and rotates together with the Earth around the N-S axis. The direction of its zenith roughly coincides with the middle of the observation strip (shadowed). EAS detected by the GAMMA array are selected in the range of zenith angles $\theta < 40°$, so that the strip is $40° \pm 40°$. Fig. 1 particularly shows that the installation does not observe the area around Polaris and the Southern Hemisphere completely. The direction of the arrow is arbitrary, so that it is given in the Galactic coordinate system $((l_0, b_0))$ in which the processing is performed. It is uniquely converted into the equatorial system.

The observed daily sunrise can be a good analog for the search of the source in such a way. Before the Sun appears above the horizon, the red color of the sunrise is already visible because of Rayleigh scattering of the light in the atmosphere. The scattering cross section is inversely proportional to the fourth power of the wavelength. Therefore the red color scatters least. With increasing of the observation angle with respect to the Sun the color of the sunrise gradually approaches the blue. Even without measuring the luminosity, the position of the Sun can be indicated by just the color. In our case it is impossible to find the source by only investigating the anisotropy of the intensity. This is why the mass composition of the PCR passing through the chaotic magnetic fields of the Galaxy can be studied. *Ceteris paribus*, the protons (analog of the red color) scatter less than nuclei (iron is the analog of the blue color). It is the reason of the separation by the rigidity of the charged nuclei making the mass composition "lighter" from the side of the source (or from the Center of the Galaxy). This example also shows how it is possible to observe the source outside its direct visibility (behind the horizon) due to the diffusion.

Use of the axially-symmetric cone is based on the almost complete randomness of the particle scattering that follows from the low anisotropy of the PCR intensity. In this scenario the PCR particles coming from the source to the Earth must have a large number of scatterings. The dawn is also visible near the horizon, where the thickness of the atmosphere is about 30 times bigger than near the zenith. At such a separation, the larger is the deviation angle of the particles from the direction to the source, the stronger they are scattered (the heavier they are).

In order to divide the events in two sets in the arbitrary direction (l_0, b_0) the following equation is applied

$$H = \cos\psi = \sin b_0 \sin b + \cos b_0 \cos b \cos(l - l_0), \tag{4}$$

where H is the cosine of the angle, ψ, between the arrival direction of the PCR particles (l, b) and the given direction (l_0, b_0) in the spherical coordinate system. It is necessary to note that events at $H \geq H_0$ are inside the cone – n^{in} and at $H < H_0$ are outside – n^{out}. The equation is valid for any spherical system including the equatorial system (α, δ) and the horizontal (laboratory) system. The general background and possible methodical errors are the same for both sets of events. Thus at $n^{in} = n^{out}$ they are automatically annihilated if subtracted. Errors made in referring the EAS to the wrong set at the interface due to errors in the angles are practically irrelevant, since the diffusion characteristics of the PCR particles are rather identical at the nearby angles of particle arrivals and are subtracted as a general background. It is not necessary to make any additional check of the event registration efficiency.

3 GAMMA installation

The test of the difference method was carried out with experimental data of the GAMMA installation obtained during 2011 - 2013. GAMMA is located on the southern slope of Mt. Aragats in Armenia at 3200 m above sea level $(700 g/cm^2)$ with geographical coordinates of the installation center of $40°28'N, 44°11'E$. GAMMA consists of a system of surface and underground detectors of charged particles. The detailed description of the installation, its technical characteristics and the main results are available in [8], [9], [10], [11].

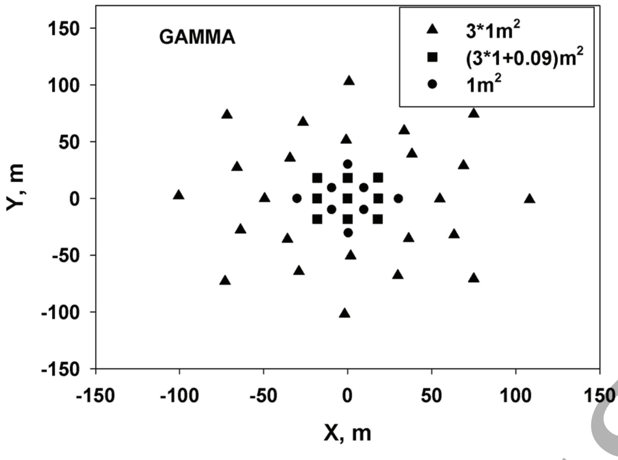


Fig. 2. Surface part of the GAMMA installation. The external radius is 100 m, the elevation - 3200 m a.s.l.

For the present analysis the information from the surface detectors has been used. The surface part, Fig. 2 consists of 41 detector points located within a circle of 100 m radius. At each point there are from one to three 5 cm thick and of 1 sq.m area plastic scintillation e/γ detectors. The minimal distances between the points are in the square of 60×60 m^2 with 17 points inside. Then there are 3 circles with radii of 50, 70 and 100 meters with 8 points in each of them. Such detector arrangements with decreasing density of the detectors from the center to the periphery provides a range of the measured PCR energy of $10^{14} \div 10^{17}$ eV using the relatively small number of detectors. EAS with minimal energy and high intensity are registered with the central detectors. The rare high energy EAS are collected from the large area but with the widely spaced detectors. The zenith and azimuthal angles were estimated with a 25 channel chronotron system.

For the present analysis we selected EAS with a number of charged particles $N_e > 10^5$, with zenith angles $\theta < 40°$ in the laboratory system and with axes within a radius $R < 60$ m from the center of the installation. The total number of events is 3.38 million for an installation run time of 11544 hours.

For the application of the difference method the following EAS characteristics were used:

- the zenith and azimuthal angles θ, φ in the laboratory coordinate system (measured resolution is 1.5°);
- EAS size N_e (resolution is $25 - 30\%$);
- the UTC arrival time (resolution is 1 sec.);
- the "lateral" age parameter S.

For each EAS the angular coordinates (θ, φ) of the arrival in the laboratory coordinate system were converted to the horizontal astronomical coordinates (A, h) in the following way: $h = 90° - \theta$ (instead of the zenith angle θ the height above the horizon has been used), the azimuth $A = 286° - \varphi$ since the "North" direction of the GAMMA installation is turned by 16° to the East relative to the real North [12], and the angles φ are calculated from "East" counterclockwise, but for horizontal astronomical system – from "South" clockwise. The arrival direction for each EAS (α – right ascension, δ – declination) for the equatorial coordinate system (epoch J2000) was calculated from the horizontal astronomical system by the standard formulae using both the geographical coordinate of the installation and the EAS arrival time. In addition, equatorial coordinates for each EAS have been recalculated to the Galactic coordinates (l – longitude, b – latitude). The correctness of the recalculation was checked by the astronomical utilities [13]. The total error of the recalculation from the laboratory system to the Galactic system is no more than 10 angular minutes for the period between 1960 and 2060, and the total accuracy of calculation of the celestial coordinates of the EAS arrival is not worse than 3°.

4 Experimental results

Apparently, the best experimental parameter in the search for anomalies is the mass composition of the PCR. However, at high energies, the composition is determined with large errors by indirect methods using the model-dependent calculations. Therefore, for the further analysis the experimental age parameter, S, has been used. The S is a dimensionless formal parameter calculated by fitting the lateral distribution function (LDF) of the particle density in e/γ detectors with the Nishimura-Kamata-Greisen (NKG) approximation:

$$\rho(N_e, r, S) = 0.366 \times N_e \frac{S^2}{r_0^2}(2.07 - S)^{1.25} \left(\frac{r}{r_0}\right)^{S-2} \left(1 + \frac{r}{r_0}\right)^{S-4.5}. \quad (5)$$

Here ρ - density of the electrons at a distance r from the EAS axis for a total number of particles, N_e, and age, S, at the observation level, $r_0 = 118$ m – the Molière radius.

Other parameterizations of the S can be different but in any case they have to characterize the steepness of the LDF. The S is correlated with the age S_{em} of the longitudinal development of the electromagnetic cascade which is used in the cascade theory: it is small at the beginning of the cascade and increases with the atmospheric depth because of multiple scattering of the EAS particles, i.e. LDF is flattening monotonically. The S parameter has a Gaussian shape of distribution and is convenient for the analysis.

The S parameter depends on the PCR mass composition because the heavy nuclei interact at a higher level in the atmosphere than protons of the same energy and the development of EAS induced by heavy nuclei is faster. Therefore at the observation level the heavy nuclei create a wider LDF with a bigger S parameter (see, for instance, [14]). The lateral S parameter is one of the basic EAS parameters and has to be well defined without application of any model. The only natural assumption in the calculation of the S is the EAS axial symmetry.

Transition from the S parameter to the mass composition requires a detailed three-dimensional calculation of the response of detectors to the EAS generated by the different primary nuclei. However, in order to search for anomalies with the difference method it is sufficient to know the sensitivity of S to the installation depth in the atmosphere, because dependence of S on the mass composition is the same for both sets of events.

The length of the geometrical path from the first interaction of the nucleon to the installation and the thickness of the atmosphere over the installation $X = X_0 \sec\theta$ ($X_0 = 700\ g/cm^2$ – the thickness of the vertical) increases with the zenith angle θ. The experimentally measured dependence of the S parameter on θ obtained with the GAMMA installation is presented in Fig. 3. An almost linear increase of S with $\sec\theta$ is seen from 0° to 40°, indicating a good sensitivity of S to the PCR mass composition.

The "blind" search of the anomalies has been carried out close to the galactic plane ($b = 0$) in the grid points with a 10° step of latitude b in the range $-30° \div 40°$. One step in the latitude is 15° in the range of $0° \div 180°$. This range is expanded up to $0° \div 360°$, because of the independence of the χ^2/J value from the sign of Δ_i.

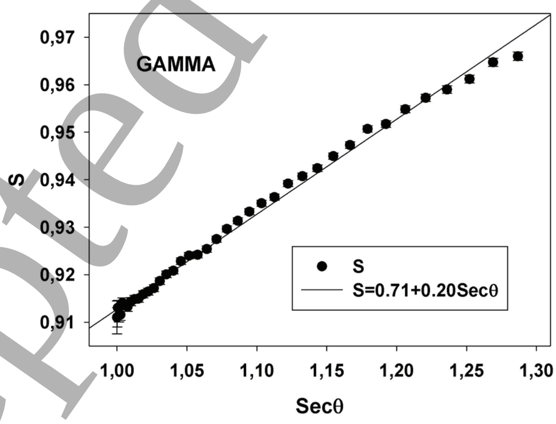


Fig. 3. Dependence of the S parameter on the zenith angle of the EAS arrival.

The dependence of χ^2/J value on coordinates l_0, b_0 is shown in Fig. 4. Only one maximum of $\chi^2/J = 57.64$ with 17 degrees of freedom is found in the di-

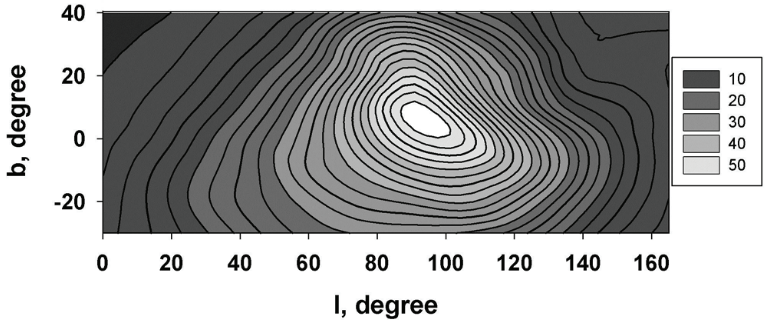


Fig. 4. Dependence of χ^2/J on the longitude l and the latitude b in the Galactic coordinate system.

rection of $l_M = 97° \pm 3°, b_M = 5° \pm 3°$. The isolines, connecting the points with equal values of χ^2/J (Fig. 4) are made without flattening but with interpolation between the grid points. The smoothness of the relief is provided by the method itself, in which the observation sphere at computing of the χ^2/J value is divided for only two sets of events. The sets substantially overlap at the relatively small shift of l_0, b_0. The step in the region of the maximum was decreased up to 2°.

Position of the maximum $l_G = 90° \pm 0.9°$, $b_G = 0.1° \pm 0.8°$ has been also obtained by fitting the normal distribution of two variables (l, b) to the maximum. Distinction of the coordinates can be connected with the incomplete axial symmetry of the relief of χ^2/J near the point of the maximum. The lack of any indications of the anomaly in the direction of the Center of the Galaxy is noteworthy $(l = 0, b = 0)$.

The value of $\chi^2/J = 57.64$ in the maximum at 17 degrees of freedom is very big. At the random spread the value of χ^2/J should be close to $1 \pm \sqrt{2/J}$, and its every increase by unity increases the statistical significance of the deviation from the case of random fluctuations by about σ.

It follows from the formulae (1) - (3) that χ^2/J must be proportional to the number of events. We were convinced by dividing the total number of events by 2, 3, 5, 10, that the value of χ^2/J is due to the large statistics and high sensitivity of the method using the total statistics at each point of the sky. In order to decrease the statistics (minimally changing the condition of the EAS registration) each second, third, fifth and tenth of the events was selected. The maximum of χ^2/J is decreased from 57.64 to 29.4, 20.3, 12.6 and 7.9 respectively, i.e. in our case at practically the same shape of the distribution the value of $(\chi^2/J) - 1$ linearly depends on the total number of the events N.

$$(\chi^2/J) - 1 \sim N \tag{6}$$

The value χ^2/J could be also systematically overestimated for any reason. In order to check this we have found the direction where χ^2/J has a minimum. The minimum equals 1.32 at $l_0 = 15°$, $b_0 = 60°$ and coincides with a random distribution of Δ/σ within the standard deviation.

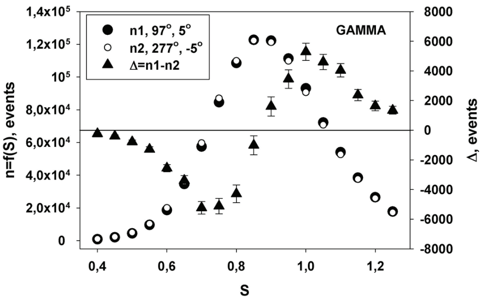


Fig. 5. The distributions of the S parameter for the direction $l_0 = 97°$, $b_0 = 5°$ and for the opposite direction. The right scale - difference Δ between them.

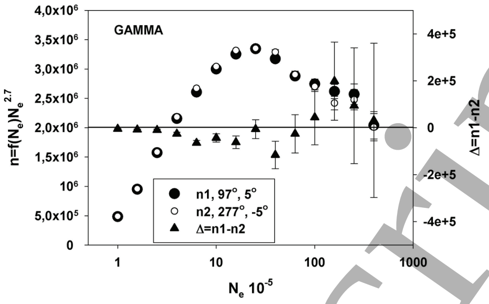


Fig. 6. The same as in Fig. 5, but for parameter $f(N_e)N_e^{2.7}$ where $N_e = 10^5 \approx 2.5 \times 10^{14}\ eV$.

Fig. 5 shows the $f(S)$ distributions in the direction of maximum for χ^2/J. The parameter $H_0 = 0.55$ when $n^{in} = n^{out}$ has been selected for this direction. It is seen in the figure that the shapes of the event distributions for the opposite directions are very close (left scale). At the same time the statistically significant difference between them (right scale) shows that the distribution for the direction $l_0 = 277°$, $b_0 = -5°$ compared with that for the direction $97°, 5°$ is shifted toward the younger EAS. Younger EAS correspond to a lighter composition of the PCR. Therefore, according to the hypothesis of separation of the PCR particles by diffusion in the magnetic fields of the Galaxy, one can assume that there is an anomaly in the direction $277°, -5°$.

Similar distributions have been obtained for the parameter $f(N_e)N_e^{2.7}$ (Fig. 6). This parameter has been chosen for binding the anomaly to the EAS primary energy in an attempt to estimate from where an excess of the PCR particles arrives. The index 2.7 is an arbitrarily chosen value to highlight the knee region. Therefore it can't be used to search for anomalies. Here $f(Ne)$ is the number of the events registered by the installation in the given range N_e without an account for any methodical effects. As noted earlier, in the difference method the general background and methodical features are automatically subtracted, as they are the same for both sets at a stable operation of the installation.

It is seen from Fig. 6 that there is a small but a statistically significant excess of the EAS at the knee region in direction $l_0 = 277°, b_0 = -5°$ confirming the hypothesis of separation of the PCR particles.

The contribution of the individual ranges by E_0 (or N_e) in the total value of χ^2/J can be obtained from the Table 1. The table shows the change of χ^2/J in the direction l_M, b_M for successive exclusions of events from the total statistics

№	Range by E_0 (PeV)	Range by $N_e \times 10^{-5}$ (excluded)	χ^2/J for the remaining number of events	Excluded number of events	Remaining number of events	χ^2/J recalculated to the total number of events
1	> 0.25	–	57.64	0	3382892	57.64
2	0.25-0.4	1.00-1.58	58.58	974928	2407964	82.30
3	0.4-0.63	1.58-2.51	47.11	873267	2509625	63.50
4	0.63-1.0	2.51-3.98	43.40	660212	2722680	53.92
5	1.0-1.58	3.98-6.31	45.17	414490	2968402	51.48
6	1.58-2.5	6.31-10.0	46.14	230405	3152487	49.51
7	2.5-4.0	10.0-15.8	52.56	120589	3262303	54.50
8	4.0-6.3	15.8-25.1	55.39	59928	3322964	56.39
9	6.3-10.0	25.1-39.8	56.94	27922	3354970	57.41
10	10.0-15.8	39.8-63.1	56.47	12314	3370578	56.68
11	15.8-25.0	63.1-100	57.09	5040	3377852	57.18
12	25.0-40.0	100-158	57.17	2169	3380723	57.21
13	40.0-63.0	158-251	57.16	917	3381975	57.18
14	> 63.0	> 251	57.16	711	3382181	57.17

Table 1

in the given ranges by E_0.

The first row is the initial data with $\chi^2/J = 57.64$. In the second row the events of the range $0.25 < E_0 < 0.4$ PeV are excluded and for the remaining events $\chi^2/J = 58.58$. After recalculation of this value for the whole statistics using the dependence (Eqn. 6) $\chi^2/J = 82.30$ (last column) was obtained which is greater than the initial value of 57.64. It indicates that the excluded range $0.25 < E_0 < 0.4$ PeV decreases the resultant value of χ^2/J.

In rows $4 - 8$ for the energy range $0.63 \div 6.3$ PeV the recalculated values of χ^2/J are smaller than the initial value. Just these ranges (especially the range with $E_0 = 1.58 \div 2.5$ PeV) make a big contribution to the resultant value of χ^2/J. For energies >6.3 PeV the small number of events does not allow us to make definite conclusions.

A similar test by calculating of χ^2/J for events of the excluded intervals is not correct because of the big recalculation coefficient and increasing errors.

The obtained result and additional check have shown that there is an anomaly in the knee region with a high statistical significance in the direction of $l_M = 277°$, $b_M = -5°$ of the galactic coordinate system ($\alpha_M = 140°$, $\delta_M = -57°$ in the equatorial system). It is caused by an excess of the lighter PCR particles from the direction of $l_M = 277°$, $b_M = -5°$ in comparison with the PCR from the opposite direction.

5 Analysis of method

The obtained statistical significance of the anomaly is very big. Therefore an additional study has been carried out to find the effects which are not taken into account.

The assumption of the smooth changes in the EAS characteristics which occur with increasing angle between the EAS arrival direction and the direction of l_M, b_M was experimentally verified. In this direction the cosine of the cone angle for the division into two equal sets of events is $H_0 = 0.55$. The EAS situated close to the boundary were excluded from the analysis and only the events for $H > 0.6$ and $H < 0.5$ have been considered. The statistics were decreased from the initial 3.38×10^6 events ($\chi^2/J = 57.6$) to 3.07×10^6 events with $\chi^2/J = 59.0$. The value of $\chi^2/J = 64.8$ was obtained by normalizing to the whole statistics using formula (6). It means that the region around the boundary is a common background which is eliminated by subtracting the distributions. Excluding the events from this region increases the statistical reliability. It also shows that possible referring the events to the wrong set due to errors in the EAS arrival angles can be ignored if the errors are not bigger than $3° \div 5°$.

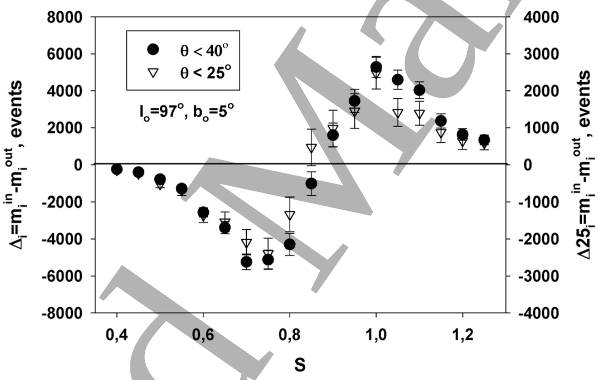


Fig. 7. Dependence of differences $\Delta_i = m_i^{in} - m_i^{out}$ on the S parameter for all the EAS (the left scale) and for EAS with $\theta < 25°$ (the right scale).

The anomaly can be imitated by the asymmetry of the installation with respect to the zenith and azimuthal angles. The range of the zenith angles θ of the used EAS is $0° \div 40°$. The conditions of the development and registration of the EAS with $\theta = 40°$ are different from the conditions for vertical EAS with $\theta = 0°$. Therefore EAS with $\theta < 25°$ (1.96×10^6 events) were selected and again the "blind" search of the anomalies has been carried out. The coordinates of the maximum as well as the shape of the distribution of the differences $\Delta_i = m_i^{in} - m_i^{out}$ in the maximum are not changed within the errors (Fig. 7). The value of the maximum has been decreased from 57.6 to 19.1, as it should be due to decreasing statistics and narrowing the selection range. It can be concluded that the coordinates and the properties of the anomaly are stable with respect to the range of the EAS zenith angles, but the narrowing of the selection range decreases the statistical significance and the confidence level of the results.

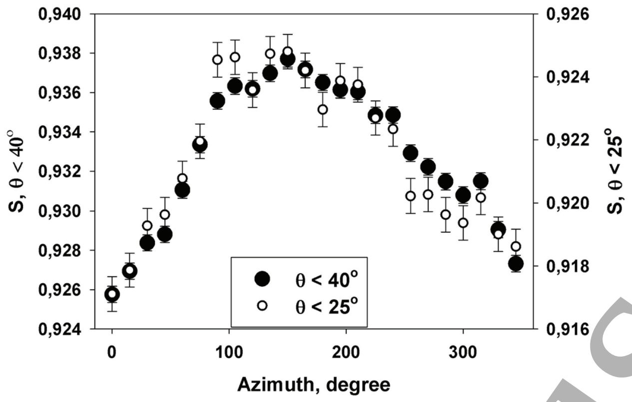


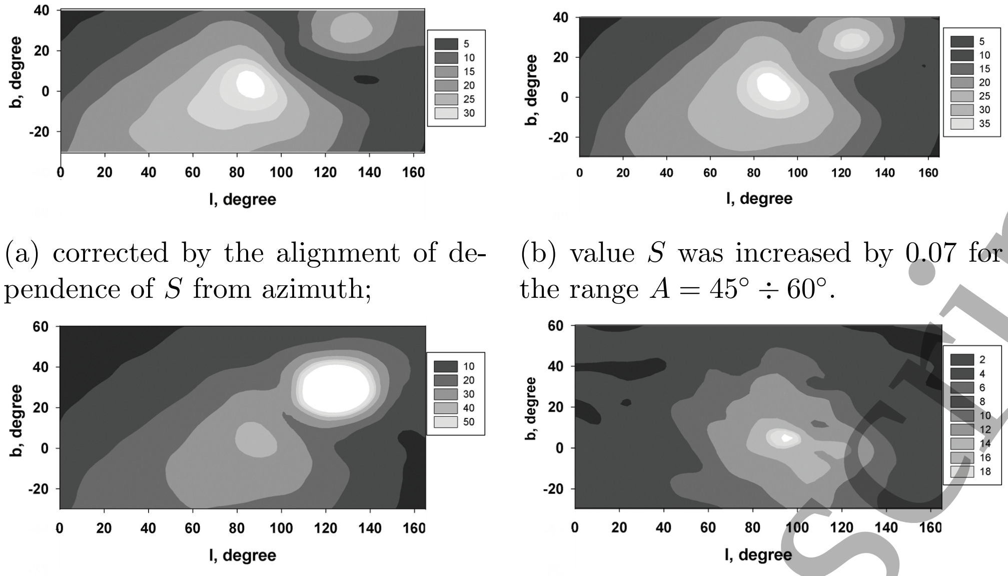
Fig. 8. Dependence of the parameter S on the azimuthal angle for EAS with $\theta < 40°$ and $\theta < 25°$

In order to test the influence of asymmetry of the azimuth angles on the anomaly, the dependence of the parameter S from the azimuth angle A in the horizontal astronomical (laboratory) coordinate system (where "0°" is directed to the South) has been obtained (Fig. 8). The small regular and almost sinusoidal dependence of S from A is observed with identical shapes for both ranges of the zenith angles θ.

This dependence can be both the cause of the anomaly and its consequence. Let us assume that the dependence $S(A)$ has arisen because of some asymmetry of the experimental installation and this is the cause of the anomaly. In this case application of the correction, eliminating the $S(A)$ dependence, should lead to the change of coordinates of the maximum or to the removal of the anomaly. To verify that possibility the corresponding corrections of $\delta(A) = S(A) - \langle S \rangle$ were subtracted from the S for all selected EAS. Then as before the anomaly has been looked for (Fig. 9a).

It is seen from Fig. 9a that the position of the main maximum did not change within the experimental errors but the value χ^2/J in the maximum decreased to 26.3. In addition, the axially symmetric second maximum $\chi^2/J = 20.3$ has appeared with coordinates $l_0 = 123°, b_0 = 27°$ which coincides with the direction of the Earth's rotation axis - the Celestial Pole.

The decrease in the main maximum and appearance of an additional maximum at the Pole mean that the application of the correction doesn't improve the initial experimental data but made them even worse imitating the asymmetry of the experimental installation. Indeed, any asymmetry of the installation in



(a) corrected by the alignment of dependence of S from azimuth;

(b) value S was increased by 0.07 for the range $A = 45° \div 60°$.

(c) value S was increased by 0.1 for the range $A = 300° \div 315°$.

(d) value S was added by random number simulated by Gaussian with the average values equal to 0 and $\sigma = 0.25$

Fig. 9. Dependence of χ^2/J from the Galactic coordinates (l, b). Contour diagrams.

a coordinate system rotating with the Earth can be divided into two components: parallel and perpendicular to the Earth's rotation axis. During the three year's operation of the installation the Earth has made more than one thousand rotations. Therefore, the component perpendicular to the axis of the installation was annihilated with a good precision as $\int_0^{2\pi} sinAdA$. This analysis points out to the coincidence of the maximum and the position of the Pole with a 1° accuracy. At the same time, the parallel component was summed up and appeared in the form of the peak.

This statement was also verified using another approach: the value of S was increased by 0.07 for all EAS with azimuth $A = 45° \div 60°$ imitating the anisotropy of the installation in this direction. The value of 0.07 was chosen to have a noticeable, but not catastrophic effect. The result is shown in Fig. 9b. It demonstrates again that the main peak did not change its position but decreased to 34.5, and again the second peak appeared at the Pole with the maximum at 34.6 due to the artificially created anisotropy. Fig. 9c shows the result when the value S was increased by 0.1 for all EAS with an azimuth of $A = 300° \div 315°$. The effect has remained qualitatively the same: the main maximum has decreased to 33.4, but the maximum on the Pole has increased to 88.2 (its top has been cut to 50 in the figure to insure the visibility of the main peak).

In order to verify that the peak occurring at the Pole is due to the asymmetry in the laboratory coordinate system, but not because of random errors in the calculations of S, a random number, which was simulated by Gaussian distribution with the mean "0" and with different σ, was added to the initial value S in all events independent of azimuth. The main maximum doesn't change its position but decreases to 42.7 at $\sigma = 0.1$ and to 19.4 at $\sigma = 0.25$ (Fig. 9d). Considering that the initial distribution of the S parameter has $\sigma = 0.16$, the stability of the position of the maximum for such big distortions demonstrates the stability of the method with respect to random experimental errors.

Returning back to Fig. 8 it can be concluded that the discovered dependence of S from the azimuth is related to celestial coordinates and indicates the arrival of "younger" EAS (lighter primary particles) from the Southern hemisphere.

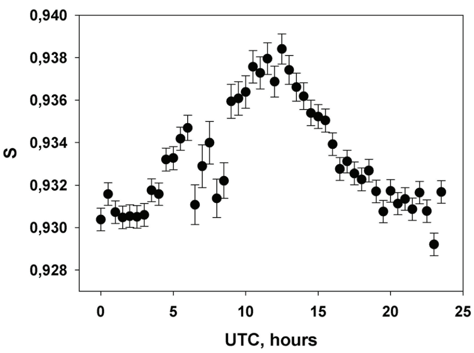


Fig. 10. Dependence of S from the time of the day in UTC. Between 5-11 hr (10-16 local time) the adjustment of the installation was performed.

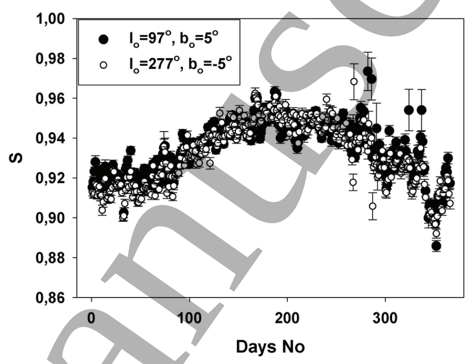


Fig. 11. Dependence of S from the day of the year for EAS set in the direction $97°, 5°$ and in opposite direction $277°, -5°$.

The solar-daily geophysical changes can also have an effect on the obtained coordinates. The dependence of S from the time of the day is presented on Fig. 10, and shows a weak regular dependence. After including a corresponding correction the maximum slightly increased from 57.6 to 58.7. Thus, the change is related to the Earth coordinate system and introduces a negligible error. The value χ^2/J on the Pole and anomaly did not change.

Earlier, (see Fig. 3), the practically linear dependence of the S parameter on $sec\theta$ was obtained. The smoothness of this dependence indicates directly that the anomaly can't imitate the geomagnetic field. The charged particles of the EAS which develops along the magnetic field tend to move along the field lines. It could lead to a narrowing of the LDF and decrease the S parameter in comparison with other EAS. The zenith angle of the magnetic field in the GAMMA region is approximately equal to 25°. Therefore an influence of the geomagnetic field should lead to the feature (dip) in the region of $sec\theta = 1.10$. There is no such feature in Fig. 3.

A regular dependence of S on the day of the year (Fig. 11) was found with an amplitude of almost an order of magnitude higher than for the sun-daily dependence. Its shape coincides with the seasonal behavior of the temperature that might be an evidence of a rather strong dependence of the S parameter on the air temperature. The S parameter distributions for the sets of events from the opposite directions coincide well. Thus, when the sets are subtracted to estimate the value of χ^2/J, dependence of S parameter from the day of the year should annihilate or to be strongly reduced. As mentioned above, in the difference method the background and methodical uncertainties are automatically annihilate since they are identical for both sets.

It should also be noted that "younger" EAS are coming from the place of the anomaly with equatorial coordinates of $\alpha_M = 140°, \delta_M = -57°$ in comparison with showers from the opposite direction. The 220^{nd} day of the year approximately corresponds to the right ascension of 140° with the almost maximum value of the S parameter (Fig. 11) that is in anti-phase with the S parameters of EAS coming from the anomaly.

6 Discussions and results

Using the difference method based on the analysis of the EAS "lateral" age parameter S the anomaly in the direction of $l_M = 277°$, $b_M = -5°$ in the galactic coordinates (equatorial coordinates – $\alpha_M = 140°$, $\delta_M = -57°$) has been discovered. The anomaly is relevant to the knee region of the PCR energy spectrum and appeared as the younger EAS coming from this region of the sky than from the opposite side. It is typical for lighter nuclei. The χ^2/J criterion used to search for the anomaly has shown a high statistical significance of the result: $\chi^2/17 = 57.6$.

The anomaly in the direction of the galaxy center has not been found.

The sensitivity of the S parameter to the PCR mass composition sufficient for the search of anomalies is confirmed experimentally by the increase of S with increasing zenith angles of EAS. It is experimentally shown that the decrease of the EAS zenith angle range (narrowing the observation band on the celestial sphere) decreases the significance of the anomaly but does not change its position. An almost complete lack of influence of the solar-daily and geomagnetic effects on the parameters of the anomaly has been experimentally obtained.

The increase of the S parameter with increasing the ground air temperature has been found and should be taken into account in the analysis of the experimental and calculated data. This dependence is completely eliminated in the difference method because it has the same influence on the EAS coming from the opposite directions.

The stability of the results has shown that an increase of the random errors of the S parameter does not change the position of the anomaly but leads to a decrease of the χ^2/J value. In the case of the errors which are asymmetric in the system rotating together with the Earth they give rise to the appearance of a maximum of the χ^2/J value in the direction of the Earth's rotation axis.

The difference method not only eliminates the background and systematic uncertainties but also allows to separate the effects associated with the laboratory coordinate system from the effects related to the fixed system of the celestial coordinates. The azimuthal asymmetry of the experimental installation is detected by the presence of a peak at the Pole, but the stable anomaly in other ranges is related, most likely, to the celestial coordinates.

The difference method does not use the simulated assumptions but only requires a stable operation of the experimental installation and applicability of diffusive transport of the particles in the Galactic scale. The presence of the diffusion follows from the practical absence of the anisotropy in many measurements of the PCR intensity in the knee energy region. It is confirmed experimentally (for the found anomaly) by removal of the angle regions near the boundary of the two sets of events. Diffusion, which is a hindrance for the traditional methods of the searching of an anisotropy, is used to study the whole celestial sphere using the installations with a limited field of view.

Nearby the discovered anomaly with Galactic coordinates $l_0 = 277°$, $b_0 = -5°$ there is a cluster in the constellation Vela with two closely located supernova remnants Vela X (263.9°, −3.3°) and Vela Jr (266.2°, −1.2°), at approximate distances from Earth of 0.3 and 0.2 kpc respectively.

It is obvious that this cluster is a good candidate for a nearby source of the PCR. The cluster is close to the direction of the detected anomaly. It is located not far from the Earth and its PCR particles have energies close to the energy of the knee. The age of the cluster is about 10^4 years and its high energy particles can reach the Earth.

Unfortunately, the difference method does not allow to determine the intensity of the particle flux coming from the source and to tell whether this source is responsible for the formation of the knee.

Some shift of the coordinates relative to the supernova remnants can be associated with the presence of the regular magnetic field between the source and the Earth, or the presence of other sources located within the limits of the resolution of the difference method, which are able to contribute to the maximum of χ^2/J.

Perhaps the registered excess of the light nuclei in the knee region explains the heavier PCR mass composition at energies above the knee observed by many other installations [15,16].

7 Conclusion

The difference method has shown its simplicity, high sensitivity and stability to random errors. The method is able to study the full celestial sphere using the facility with the limited field of view in the laboratory coordinate system, as well as to separate anomalies in the system of coordinates related with the daily rotation of the Earth from the anomalies in the celestial coordinates. The observed anomaly is a good candidate for a nearby source of the PCR responsible for the formation of the knee in the PCR energy spectrum.

The main difference from traditional methods is a study of the EAS characteristics in the different directions, and not their intensity. Together with the age parameter, S, other EAS experimental characteristics and their combinations can be used for this purpose.

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